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EVALUATION OF MINIATURE SINGLE-WIRE SHEATHED THERMOCOUPLES FOR TURBINE BLADE TEMPERATURE MEASUREMENT

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16 Abstract

An investigation was made of miniature, single-wire sheathed thermocouples for application to jet-engine turbine blade temperature measurement. Chromel-Alumel thermocouples were used, with sheath diameters of 0.15 and 0.25 mm. Tests were conducted at temperatures ranging from 750 to 1250 K. Both steady-state and thermal cycling tests were performed for times up to 200 hours. Initial testing was performed in a low velocity gas stream for long time periods using a Meker-type burner. Additional testing was done in a high-velocity gas stream for short time periods using a hot-gas tunnel and also in a J75 jet engine. A total of eleven 0.15 mm diameter thermocouples and six 0.25 mm diameter thermocouples were tested. Drift rates up to $2\frac{1}{2}$ percent in 10 hours were observed. Photomicrographs show that this design is near the limit of miniaturization based on present manufacturing capabilities. Results indicated that the effects of miniaturization on reliability and accuracy must be considered when choosing thermocouples for a particular application

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SUMMARY

An investigation was made of miniature, single-wire sheathed thermocouples for application to jet-engine turbine blade temperature measurement. Chromel-Alumel thermocouples were used, with sheath diameters of 0.15 and 0.25 mm. Tests were conducted at temperatures ranging from 750 to 1250 K. Both steady-state and thermal cycling tests were performed for times up to 200 hours.

Initial testing was performed in a low velocity gas stream for long time periods using a Meker-type burner. Additional testing was done in a high-velocity gas stream for short time periods using a hot-gas tunnel and also in a J75 jet engine. A total of eleven 0.15 mm diameter thermocouples and six 0.25 mm diameter thermocouples were tested. Drift rates up to $2\frac{1}{2}$ percent in 10 hours were observed. Photomicrographs show that this design is near the limit of miniaturization based on present manufacturing capabilities. Results indicated that the effects of miniaturization on reliability and accuracy must be considered when choosing thermocouples for a particular application.

INTRODUCTION

The purpose of this investigation was to evaluate the performance of miniature single-wire sheathed thermocouples for turbine blade temperature measurements. A thermocouple was formed with two single-wire sheathed thermoelements placed side by side in a shallow groove machined into the blade surface. The groove is then covered, restoring the aerodynamic surface. Because of this installation procedure, the blade wall thickness is the limiting factor for thermocouple groove depth.

As blade walls get thinner due to complex cooling geometries, thermocouple grooves must also be minimized. By placing each thermoelement in a separate sheath, thermocouple outside diameter and therefore groove depth is minimized for a given inter-element insulation thickness compared to the conventional design, which has both thermoelements in the same sheath. It is this inter-element insulation thickness which must be maximized to maintain the reliability of this thermocouple design. The disadvantages of the single-wire sheathed design are greater thermocouple mass and broader groove width. In most applications, these are acceptable tradeoffs.

The previous work of reference 1 tested two-wire and single-wire Chromel-Alumel sheathed thermocouples in sizes from 0.76 mm down to 0.25 mm sheath diameter in low velocity gas stream tests in the range from 1080 to 1250 K. The purpose of the present tests was to evaluate smaller size thermocouples and to extend the range of test conditions to high velocity gas streams using a hot-gas tunnel and a jet engine. Type K (Chromel-Alumel) single-wire sheathed thermocouples of special-order 0.15 and commercial-grade 0.25 mm outside diameter were tested. Testing took place in a temperature range from 750 to 1250 K. Tests were conducted at low gas velocity using a Meker-type burner, in a hot gas tunnel at Mach number of 0.4, and in a J-75 engine with thermocouples mounted on turbine rotor blades.

APPARATUS AND TEST PROCEDURES

The apparatus for these experiments consisted of the thermocouples, the simulated and actual blades on which they were mounted, and the facilities in which they were tested. Table I summarizes the scope of this test program.

Thermocouples

The thermocouples used in these experiments were Chromel-Alumel with magnesium oxide insulation and inconel sheaths. Each thermoelement was in a separate sheath. They were purchased under standard commercial-grade manufacturer's specifications including ±3/4 percent limit of error. Two sizes were used, with sheath diameters of 0.25 and 0.15 mm. The 0.25 mm sheath diameter was an actual commercial-grade thermocouple, but the 0.15 mm size was a special-order which had not previously been manufactured. These thermocouples are formed by the drawing process, in which the assembly of sheath, crushable ceramic, and wire are drawn through a series of size reduction dies, with an annealing step between each drawing, until the desired size is attained. Figure 1 shows the nominal values of wall thickness, wire size, and insulation thickness as a function of sheath diameter, as given in reference 2, compared to the more commonly used two-wire sheathed thermocouple configuration. The figure also shows that the inter-element insulation thickness is increased by a factor of $2\frac{1}{2}$ for the same outside diameter when comparing single-wire to two-wire sheathed geometries.

Photomicrographs of 0.15 and 0.25 mm outside diameter single wire sheathed thermoelements magnified ×100 and ×250 are shown in figure 2. The 0.25 mm sheathed assembly appearance (fig. 2(a)) is similar in quality to previous photos taken of larger diameter wire and shows no signs of deterioration as a result of the drawing process. The 0.15 mm sheathed assembly (fig. 2(b)) shows marked degradation of both wire and sheath, and the theoretically expected inter-element insulation distance (fig. 1) is not achieved. From the figure, it is judged that this dimension may be reduced by a factor of about two.

Acceptance tests. - The thermocouple acceptance checking procedures are described in detail in reference 3. They include a sheath integrity test, an insulation resistance test, a thermocouple homogeneity or spurious emf test, and a junction integrity test. The acceptance testing procedure was modified for the spurious emf tests for the single-wire thermocouples. Here, the two ends of the same wire formed the circuit, and deviations from zero output were observed as a flame is passed over the length of the sheathed wire assembly. All the thermocouples used in these tests were subjected to the same rigid acceptance checks and were installed by the same person in the most repeatable manner possible.

Installation technique. - Figure 3 shows a typical single-wire sheathed thermocouple installed in a groove in the wall of a turbine blade. A cross-sectional sketch of the thermocouple away from the junction is shown in figure 3(a). The two sheathed thermoelements are laid side by side in the rectangular groove after a small amount of insulation has been removed from the open ends of each assembly. This allows the single wires from each assembly to be placed in closer proximity to each other prior to end closure. A contoured peening tool is then applied to flatten the tubes at the junction region. The flattened end (fig. 3(b)) is then laser- or spot-welded to form a seal and also to secure the thermocouple to the bottom of the groove. This multipurpose operation forms the thermocouple junction, seals the ends of the thermoelements, and thermally and mechanically attaches the junction region to the blade. The groove void above the junction region is filled in with a contoured metal slug. Then a thin cover plate (fig. 3(a)), whose top surface is approximately flush with the blade surface, is spot-welded along the surface edges of the remainder of the groove. This cover plate retains and protects the thermocouple sheath and maintains the aerodynamic blade surface, but still allows free expansion of the assembly.

Test Blades

Simulated turbine test blades. - Two types of simulated test blades (fig. 4) were used, one for Meker burner testing and one for hot gas tunnel testing.

The type used in Meker burner testing is shown in figure 4(a). The front of the test blade contained three rectangular grooves down the center of the span in which three thermocouples were installed. The thermocouple junctions were located $2\frac{1}{2}$ centimeters from the right end of the blade. A test flame was applied to the front of the blade. The back of the blade has a bare-wire reference thermocouple spot-welded to the surface opposite the center test thermocouple junction. Platinum foil radiation shields (not shown) were placed over the area of the reference thermocouple junction to equalize the indicated temperature on the two sides of the blade. Holes were drilled in the blade to inhibit chordwise heat flow and thus provide a more uniform temperature in the junction region. The blade was about $1\frac{1}{2}$ millimeters thick. This blade type was used in blades 1 and 2 (table I).

The simulated test blade used in the hot gas tunnel tests is shown in figure 4(b). Blade shape was changed to meet the requirements of the test section of the tunnel. Two test thermocouples are mounted on the front surface of the blade $2\frac{1}{2}$ cm from the end of the blade and a reference thermocouple is mounted on the back of the blade directly between the test thermocouples. This blade type was used in blade 3 (table I).

J-75 Engine turbine blade. - An instrumented J-75 turbine blade is shown in figure 5. Thermocouple installation on the blade airfoil was the same as previously described. Thermocouple junctions are located at midspan, 3 per blade, at a distance of 0, 0.6, and 1.2 cm from the trailing edge. Reference thermocouples were mounted on the two adjacent blades at the midspan trailing edge. Blades 4, 5, and 6 (table I) were J-75 turbine blades.

Facilities and Test Procedures

Meker burner test apparatus. - The simulated blade assembly for burner testing was cantilever mounted with the span and chord lines in a horizontal position (U channel facing up) over a Meker burner. The natural gas and air burner produced a flame which was $2\frac{1}{2}$ centimeters in diameter. The burner was always centered at the midchord position during heating. The blade mounting support could be moved to locate the blade over the burner at various span positions.

For cyclic heating the burner was pneumatically actuated to and from the blade. An automated timing system cycled the burner every 6 minutes. This cycle time was long enough to allow the blade to reach and maintain the desired temperature but short enough to allow life cycling data to be obtained. Self-balancing strip-chart potentiometers were used to record the test and reference thermocouple output continously. Steady state and cyclic tests were performed with test blades 1, 2, and 3.

Hot tunnel test apparatus. - Thermocouples on test blade 3 were tested in a high-temperature tunnel which was basically a steady-state combustor. This facility uses natural gas as a fuel and is capable of producing test section conditions of Mach 0.2 to 0.9 at gas temperatures from 810 to 1860 K and at total pressures from 0.05 to 0.2 megapascal (0.5 to 2 atm). The reference probe used to determine total temperature was a double-shielded aspirated probe. When a steady-state point was achieved in the system, this reference probe was actuated into the stream to determine tunnel conditions.

J-75 Turbine engine. - Views of the J-75 turbine engine are shown in figures 6(a) and (b). The J-75 turbine rotor blades are shown mounted in the engine in figure 6(a). The view is looking upstream at the trailing edge and suction side of the blades. The turbine had 76 blades and a tip diameter of 81.2 cm. The blades had a span of 10.2 cm and a chord length at midspan of 4 cm. During the tests the engine was operated at idle (1005 K turbine-inlet-temperature) and at various operating points in the 1450 to 1616 K turbine-inlet-temperature range. The tip speed of the blades was about 260 meters/sec at idle and about 370 meters/sec in the operating range.

A closeup of the test blade section for the 0.25 mm thermocouple experiment is shown in figure 6(b). Six test thermocouples are mounted at the midspan on blades 5 and 6 and reference thermocouples are mounted on the trailing edge of the two adjacent blades. Maximum blade temperature varied from 1127 to 1181 K at the operating points of the engine. Blade temperature is partially controlled by adjusting internal cooling airflow. Maximum blade temperature at idle is about 870 K. The ceramic coated blades in the figure were associated with other experiments involving optical pyrometry. Blade 4, with 0.15 mm thermocouples, was tested in the same manner at a different time.

A shaft data system was used to transfer the signals from the thermocouples on the rotating turbine blades across the rotating-to-stationary interface. This system is described in reference 4.

RESULTS

The test results are presented as thermocouple drift where drift is defined as the gradual change in the emf output of the thermocouple with time due to physical or chemical degradation, and is presented as the difference between test thermocouple temperature and reference thermocouple temperature. Drift depends upon thermocouple size, quality of materials, fabrication and installation techniques, and test conditions. Reference thermocouples were recalibrated after testing to verify their stability.

Table I is a summary of the blades and thermocouples used in the tests. Blades are identified by number in chronological order of testing. A total of six blades and 17 thermocouples were tested, consisting of eleven 0.15 mm diameter and six 0.25 mm diameter sizes.

Meker Burner Tests

Initial testing of the 0.15 mm thermocouples was performed on blades 1 and 2 in a Meker-type burner at low velocity. The goal was to simulate temperature, thermal cycling, and life testing in a rapid and inexpensive manner. Three 0.15 mm thermocouples along with a reference thermocouple were installed in each of two test blades of the type shown in figure 4(a).

The results obtained with test blade 1 are shown in figure 7. The test consisted of 28 hours of steady-state testing at 1140 K; 20 thermal cycles from near room temperatures to 1140 K; 15 hours of steady state testing at 1260 K; and 100 hours of steady-state life testing at 1140 K. The results show initial drift rates of about 1 percent per 10 hours at 1140 K; about 2 percent per 10 hours at 1260 K; 1 failure (open junction) in the 4th hour of the final 100 hour test; and long term drift rates of about 1/2 percent per 10 hours during the 100 hours at 1140 K.

The results of test blade 2 are shown in figure 8. The test consisted of 4 50-hour periods of steady-state temperature at increasing temperature levels of 870, 1000, 1140, and 1260 K. The results show a negligible drift rate at 870 K and a slight drift rate of 1/4 percent per 10 hours at 1000 K. At 1140 K, thermocouples 1 and 2 show a drift rate of 1/2 percent per 10 hours while thermocouple 3 averaged about 1 percent per 10 hours. At 1260 K thermocouples 1 and 2 drifted at 3/4 percent per 10 hours while 3 went through an unexpected change in drift direction before settling to a 1/2 percent per 10 hours drift rate. After 225 hours of testing, one thermocouple experienced a junction failure. The other two thermocouples were still operating at 245 hours.

Hot Tunnel Test

For testing in a hot-gas tunnel (steady-state combustor), two test thermocouples and a reference thermocouple were mounted in test blade 3 of the type shown in figure 4(b). The purpose of the test was to simulate high gas velocity and the resultant aerodynamic loading. The results of the test are shown in figure 9. Ther thermocouples were run in the hot gas tunnel at a steady-state temperature of 980 K for 1/2 hour and 1170 K for 3 hours at a Mach number of 0.4. The time period was too short to obtain a measurable drift rate. One thermocouple junction failed during the cool-down at the conclusion of the test (first thermal cycle). The test blade was also run in the Meker burner for 10 hours to check the results including 2 additional thermal cycles. The failed junction remained open and the other thermocouple drifted about 1 percent per 10 hours.

J-75 Engine Tests

Thermocouples were also mounted in turbine blades and tested in the J-75 engine; 0.15 mm thermocouples were tested on blade 4 and 0.25 mm thermocouples were tested on blades 5 and 6.

Figure 10 shows the results for blade 4 which had three 0.15 mm thermocouples mounted at the midspan at distances of 0, 0.6, and 1.2 cm from the trailing edge. A reference thermocouple was mounted at the midspan trailing edge location of an adjacent blade. This gives a direct comparison for thermocouple 1 assuming that adjacent blades have the same temperature distributions, while thermocouples 2 and 3 have an initial displacement caused by the temperature gradient across the blade. Thermocouples 2 and 3 were about 125 and 225 K cooler than thermocouple 1, respectively. Deviations from this initial displacement value (indicated by solid symbols) represent drift. Total time of the test was $20\frac{3}{4}$ hours with 7 hours at idle conditions and $13\frac{3}{4}$ hours at operating points. The test was divided into 6 separate test runs. Thermocouples 1 and 2 failed after 6 hours during the second thermal cycle. Thermocouple 3 which reached a maximum temperature of 925 K, was operating at the end of the 20 hour test and had drifted slightly.

The two failures were traced to the lead-wire splice on the root of the blade. The ceramic cement used to protect the splice region did not hold up in the severe environment (fig. 11). To solve this problem, the splice region was moved below the platform on the last two blades where the environmental conditions are less severe. There were no further failures of this type.

Blades 5 and 6 had three 0.25 mm thermocouples each mounted in the identical manner as blade 4 (0.15 mm thermocouples) with the exception of the relocated splice. These two blades were tested simultaneously. One thermocouple (No. 2 on blade 5) suffered an installation failure, leaving five thermocouples for the test. The test lasted 21 hours, with 7 hours at idle conditions and a blade trailing edge temperature of about 800 K, and 14 hours at operating speeds and about 1150 K at the same location. The test was divided into seven runs and therefore seven thermal cycles. Figure 12 shows the drift of the thermocouples on blades 5 and 6. The two trailing edge thermocouples showed drifts of about 1/2 to $1\frac{1}{2}$ percent per 10 hours. The thermocouple which was 0.6 cm from the trailing edge was about 125 K cooler and the two thermocouples 1.2 cm from the trailing edge were about 200 K cooler. These three thermocouples experienced negligible drift with about ± 20 K scatter in the data. There were no failures during testing.

DISCUSSION OF RESULTS AND CONCLUDING REMARKS

Some general comments can be made about the results of the tests reported herein. The onset of measurable drift of the thermocouple installation was determined to occur at a temperature of about 1000 K. In the range from 1088 to 1250 K, drift rates varied from nearly negligible to about $2\frac{1}{2}$ percent per 10 hours in a fairly random manner. This amount of unpredictability of drift is more pronounced in these smaller sizes compared to previous tests of larger size sheathed thermocouple assemblies (ref. 1). Low velocity gas streams provide a good simulation of these drift rates but not of failure rates in actual engines. Failure rates were greater in the more severe engine environment. The predominant failure mode in all tests was open circuit during thermal cycling.

Photomicrographs of the 0.15 and 0.25 mm sheathed thermocouple assemblies showed that the 0.25 mm thermocouple conforms closely to the nominal dimensions shown in figure 1. The 0.15 mm thermocouple was considerably degraded by the drawing process, leaving about half of the theoretically predicted sheath-to-wire insulation spacing. This must have an adverse effect on reliability. It also shows that 0.15 mm is near the limit of miniaturization of this configuration for the drawing process used.

These thermocouples can be used in situations where the accuracy and reliability requirements are compatible with the uncertainty in drift. If post-test calibration is possible, much of this uncertainty could be eliminated and the types of applications could be increased.

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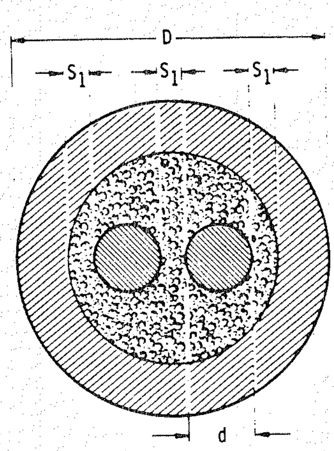
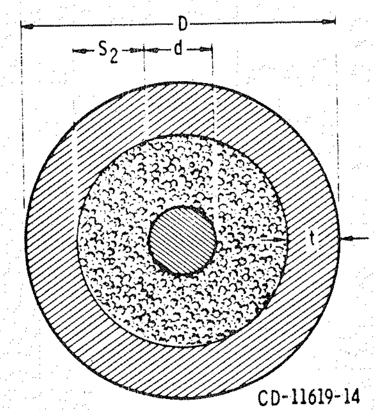
TABLE I. - SUMMARY OF BLADES AND THERMOCOUPLES USED IN TEST

Blade number	Blade type	Test thermocouples (fig. 3) (single-wire sheathed Chromel-Alumel)	Reference thermocouple	Test facility	Results
1	Simulated test blade (fig. 4(a))	Three 0.15 mm diam	0.9 mm diam two-wire ceramic insulated C-A	Meker burner	Fig. 7
2	Simulated test blade (fig. 4(a))	Three 0.15 mm diam	0.9 mm diam two-wire ceramic insulated C-A	Meker burner	Fig. 8
3	Simulated test blade (fig. 4(b))	Two 0.15 mm diam	0.9 mm diam two-wire ceramic insulated C-A	Hot gas tunnel and Meker burner	Fig. 9
4	J-75 turbine blade (fig. 5)	Three 0.15 mm diam	0.5 mm diam two-wire sheathed C-A	J-75 engine	Fig. 10
5	J-75 turbine blade (fig. 5)	Three 0.25 mm diam	0.5 mm diam two-wire sheathed C-A	J-75 engine	Fig. 12
6	J-75 turbine blade (fig. 5)	Three 0.25 mm diam	0.5 mm diam two-wire sheathed C-A	J-75 engine	Fig. 12

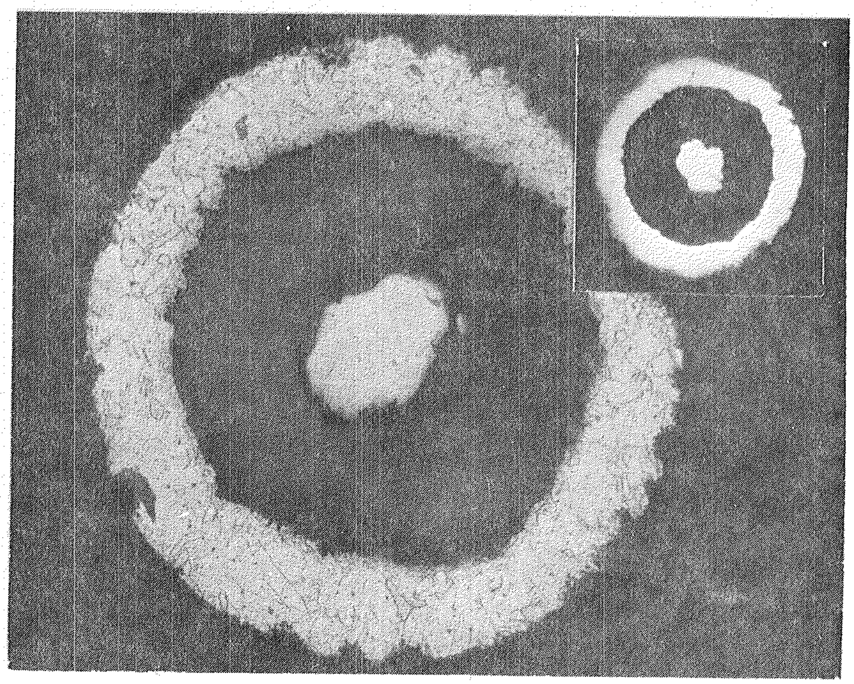


(a) Two-wire sheathed thermocouple.

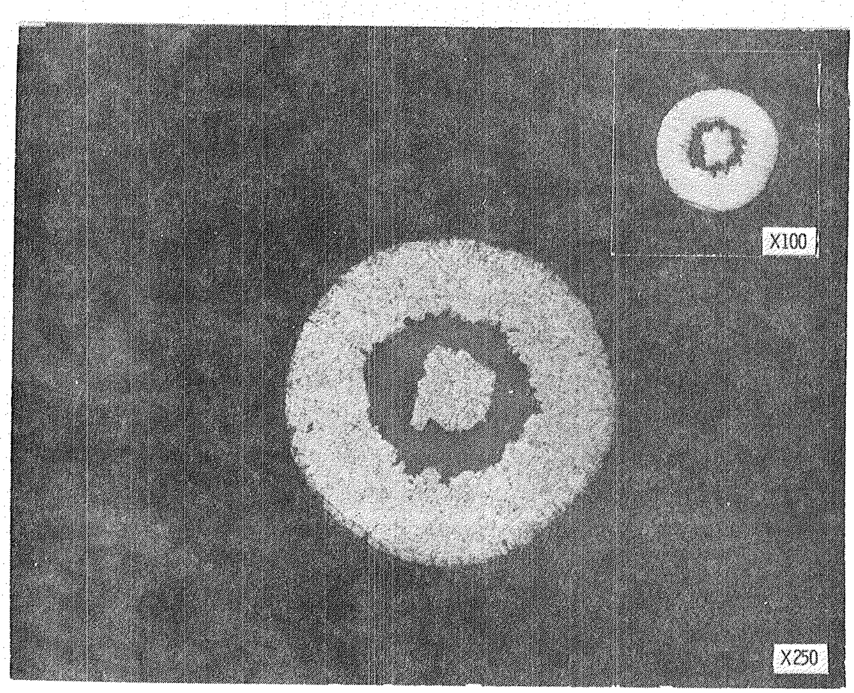


(b) Single-wire sheathed thermoelement.

Figure 1. - Comparison of geometry of a two-wire sheathed thermocouple and a single-wire sheathed thermoelement. Nominal values (from ref. 2): $t = 0.16\ D$ and $d = 0.19\ D$; example: for $D = 0.25$ millimeter, $d = 0.05$, $t = 0.04$, $S_1 = 0.025$, and $S_2 = 0.06$ millimeter.

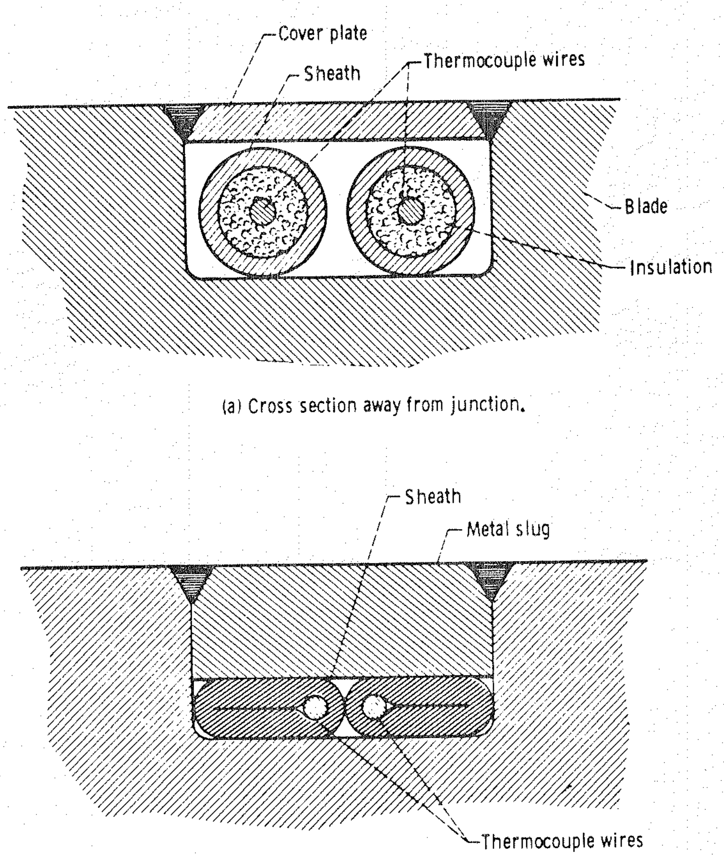


(a) 0.25 Millimeter outside diameter.



(b) 0.15 Millimeter outside diameter.

Figure 2. - Photomicrographs of two sizes of single-wire sheathed thermoelements. Inserts are unetched.



(a) Cross section away from junction.

(b) Cross section at sheath end closure.

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Figure 3. - Thermocouple formed with two sheathed thermoelements in blade groove. Single-wire sheathed thermocouple.

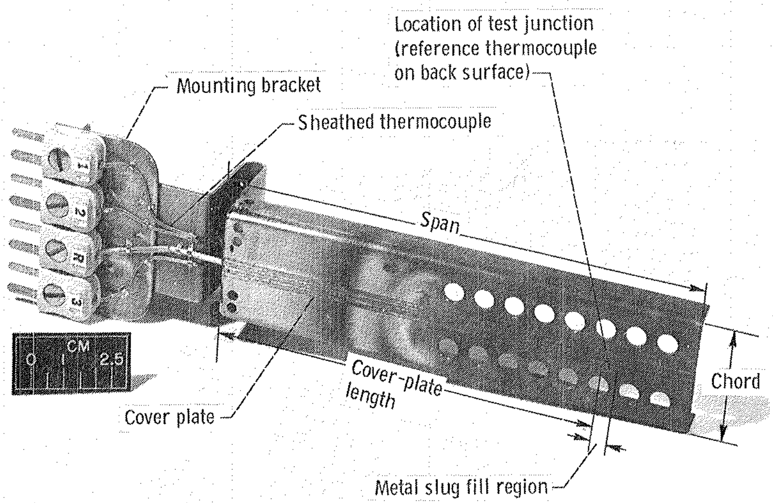

Figure 4(a). - Instrumented simulated turbine test blade for Meker burner testing.

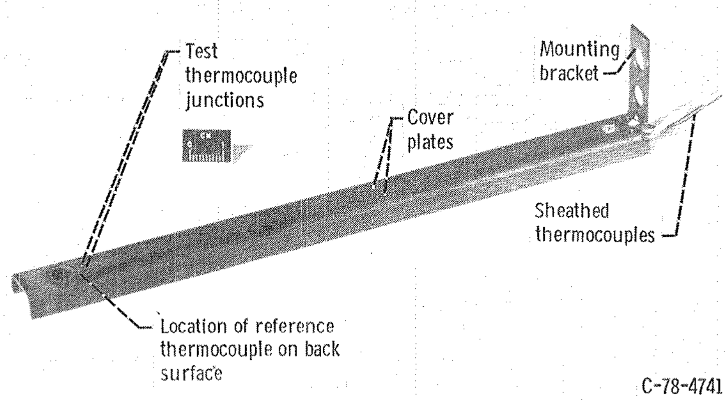

Figure 4(b). - Instrumented simulated turbine blade for hot gas tunnel testing.

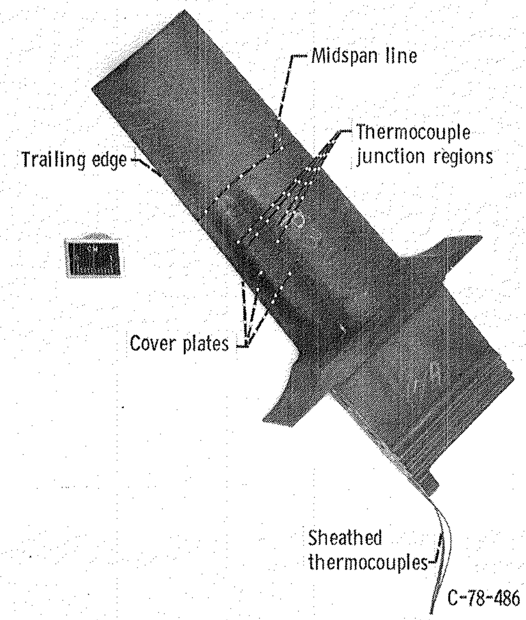

Figure 5. - Instrumented J-75 turbine test blade.

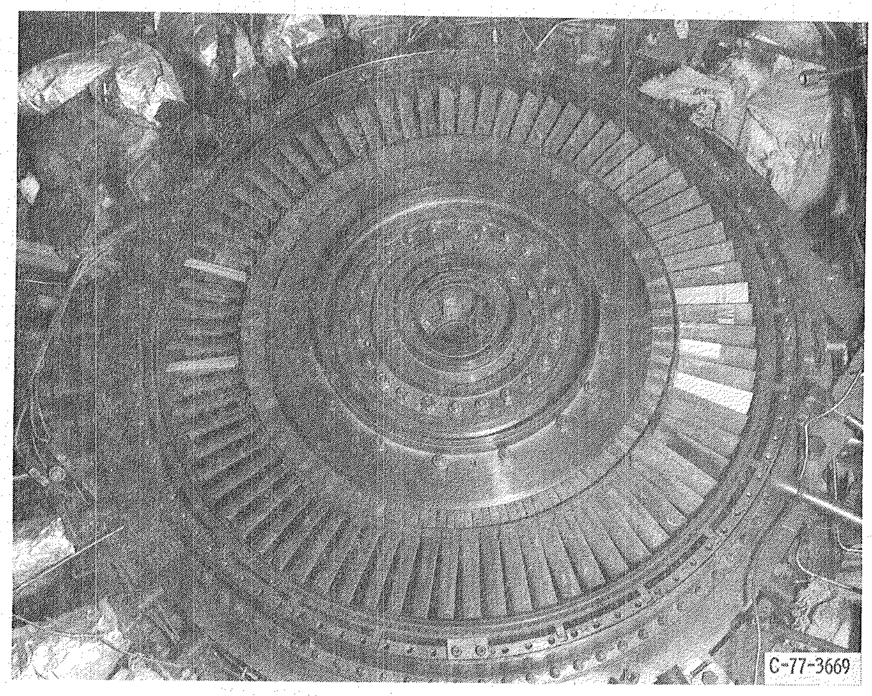

Figure 6(a). - J-75 engine turbine rotor.

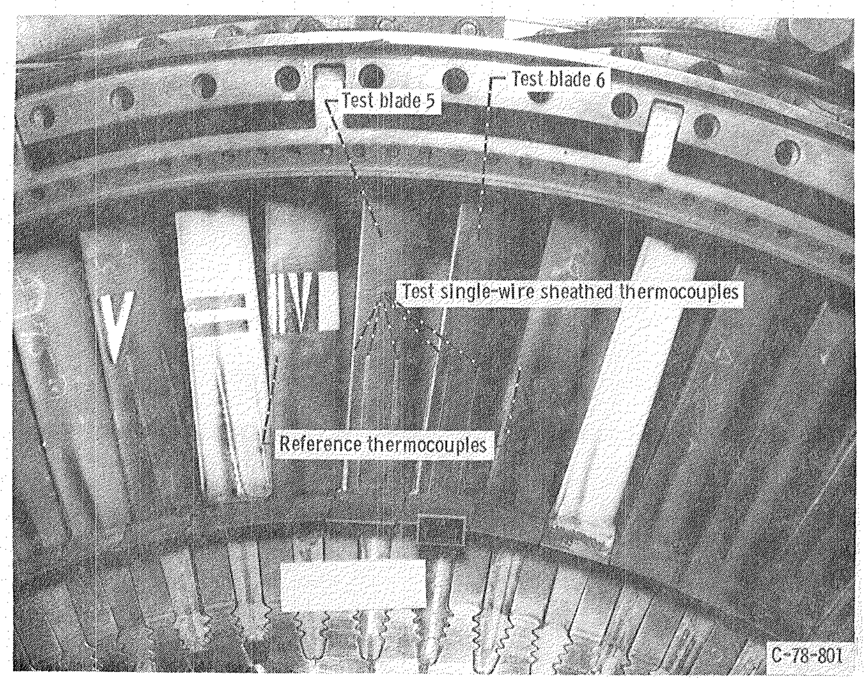

Figure 6(b). - Instrumented test blades mounted in turbine rotor.

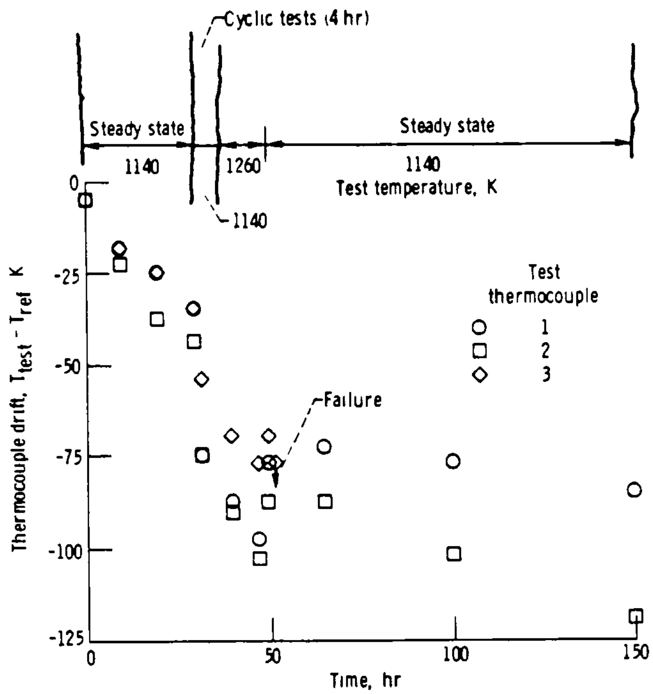

Figure 7 - Drift of single-wire Chromel-Alumel sheathed thermocouples Sheath diameter, 0.15 millimeter, test blade 1

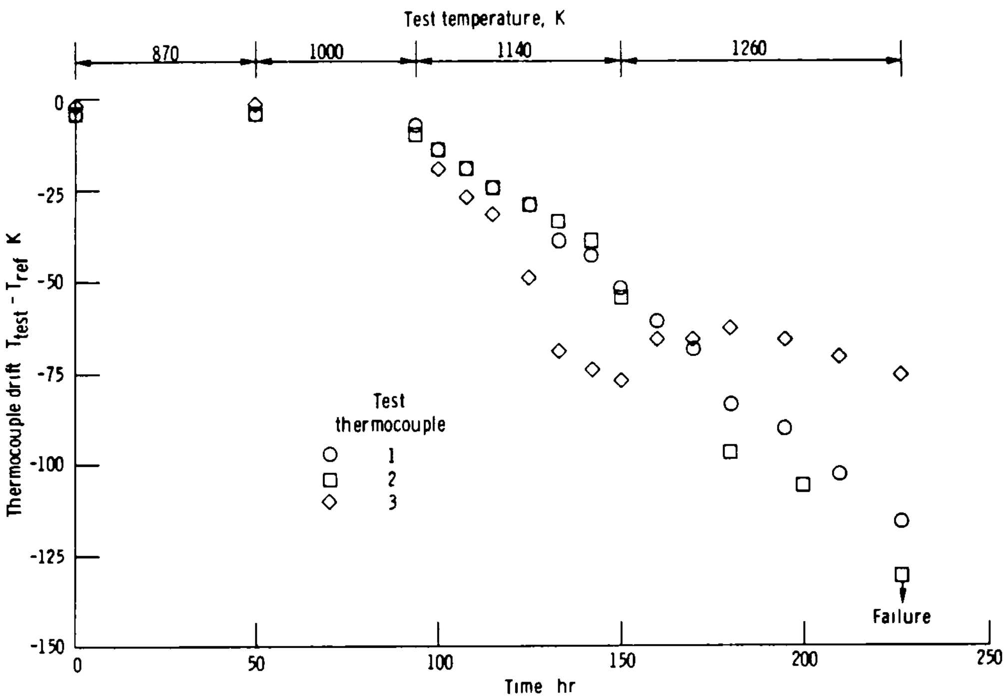

Figure 8 - Drift of single-wire Chromel-Alumel sheathed thermocouples Sheath diameter, 0 15 millimeter, test blade 2

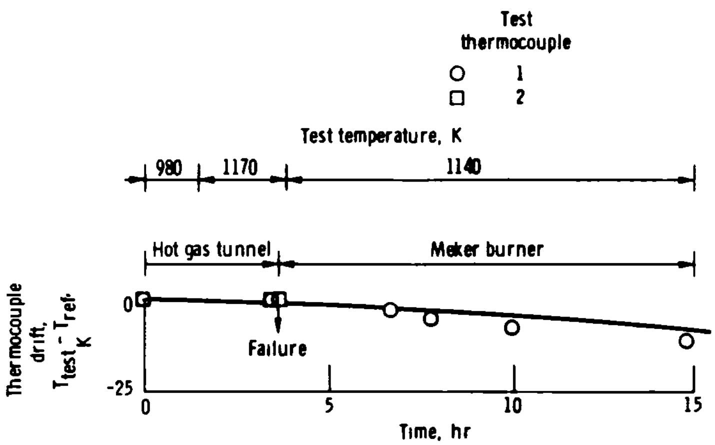

Figure 9 - Drift of single-wire Chromel-Alumel sheathed thermocouples Sheath diameter, 0 15 millimeter, test blade 3

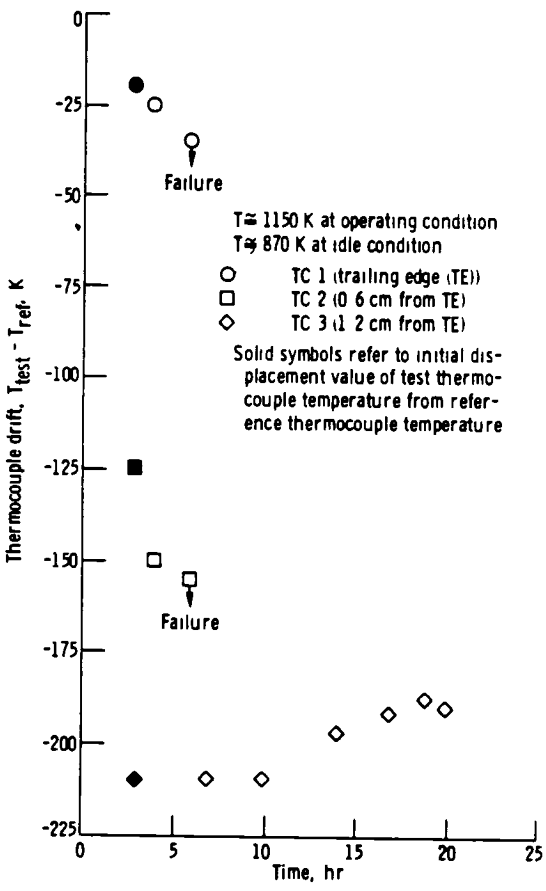

Figure 10 - Drift of single-wire Chromel-Alumel sheathed thermocouples on J-75 engine turbine blade Sheath diameter = 0.15 millimeter, test blade 4.

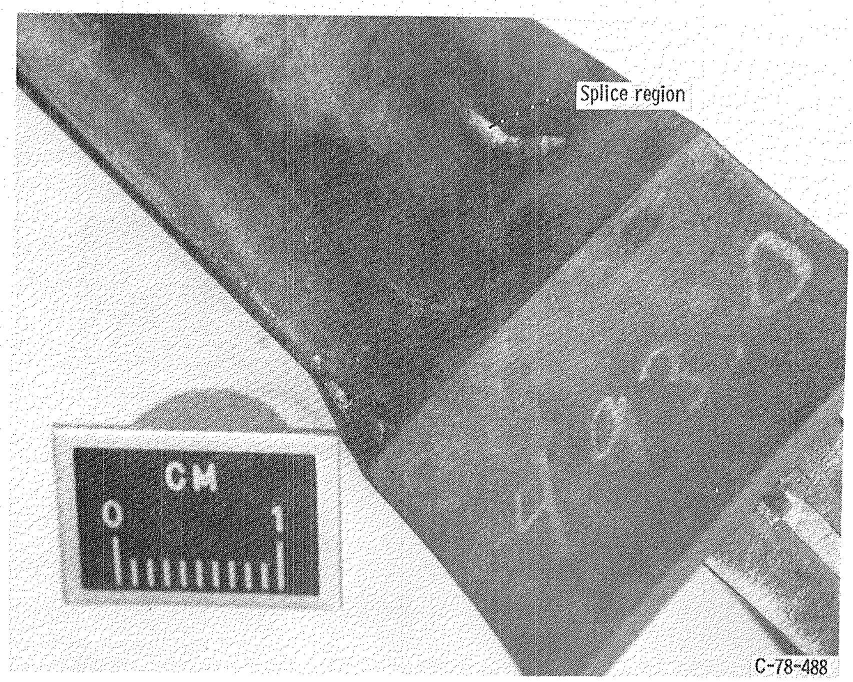

Figure 11. - Thermocouple failure at splice region near root of turbine blade.

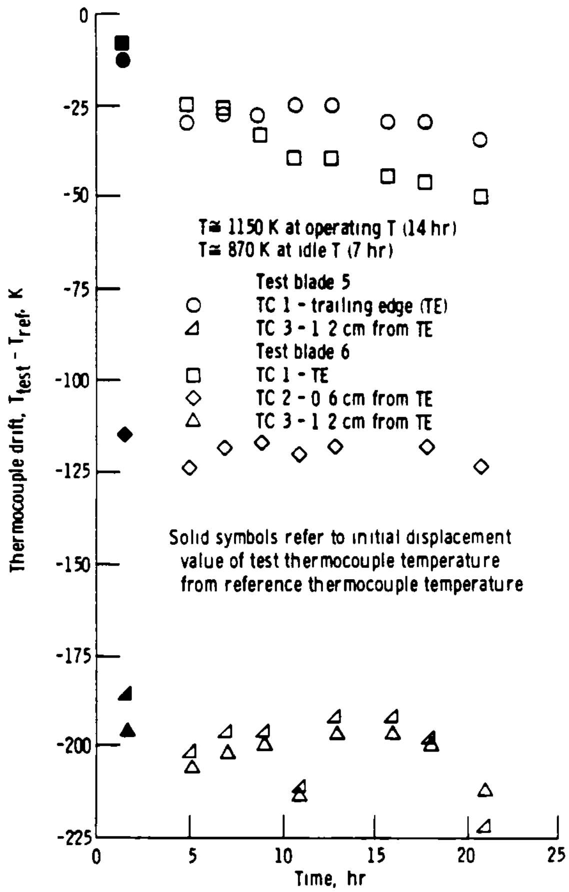

Figure 12 - Drift of single-wire Chromel-Alumel sheathed thermocouples on J-75 engine turbine blades Sheath diameter, 0 25 mm, test blades 5 and 6

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